MESUR PATHFINDER MICROROVER FLIGHT EXPERIMENT: A STATUS REPORT'

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Case For Mars V Conference
Boulder, Colorado
26-29 May 1993

' The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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MICROROVER BACKGROUND

Mars Rover missions have been studied since about 1985, primarily in conjunction with Mars Sample Return (References 1, 2) or as precursor explorers for human missions (References 3, 4, 5). Until 1989 the rovers envisioned for these missions were large (800-1000 kg), highly autonomous, and were intended to rove as much as hundreds of kilometers, returning a geologically diverse set of samples to a large earth return vehicle. Mars Rover Sample Return (MRSR) was conceived as having an imaging orbiter to provide high resolution pictures to ensure safe landing sites for the costly rover and sample return landers. The total cost of MRSR was estimated to be about $1 OB.

Large rovers were also thought of as site characterization precursors to human missions, autonomous vehicles which could scout out safe human landing sites, locate resources, and even prepare sites for human exploration. Rovers were also envisioned as field geology assistants for human outposts on Mars, providing "telepresence" at remote sites for geologists located at a base camp (Reference 6).

In 1989-1992, despite President Bush's announcement of a Space Exploration Initiative, and despite efforts such as those of the Synthesis Group (Reference 7), funding for human missions and their robotic precursors was not only not increased to the scale required for the large Mars Rover Sample Return missions, but was steadily cut by Congress, This funding shortfall forced innovative concepts to be developed for Mars Rovers, and the most promising of these concepts focussed around small ("mini" to "micro") rovers in the 5 to 50kg class.

Four factors contributed to the feasibility of small rovers:

1. The worldwide miniaturization of electronics,
2. The availability of small, extremely mobile chassis developed as test models for the large rovers at JPL (Reference 8).
3. The development of insect-like autonomous control algorithms, initiated by Rodney Brooks of MIT with his "subsumption architecture" and extended by David Miller and others at JPL (Reference 9).
4. The development of the "Computer Aided Remote Driving" technique of

remote operator control at JPL (Reference 10).

These factors were combined at JPL in a series of experiments where increasing smaller computers and increasingly sophisticated sensors were mounted on increasingly capable “Rocker r-Bogie” chassis. Called “Rocky” for short, this series culminated in a demonstration in June 1992 of “Rocky 4“ in the Arroyo Seco next to JPL. The Rocky 4 demonstration, led by Dr. Lonne Lane, proved the concept of an integrated microrover system (7 kg including instruments) which could conduct useful science experiments in rugged terrain, with a combination of earth operator designation of targets and tasks, and autonomous, on-board control for task execution, path following and hazard avoidance.

The success of this demonstration led to a submission by JPL and OACT (Office of Advanced Concepts and Technology) to the FY94 NASA budget of a MESUR Pathfinder Microrover Flight Experiment (MFEX). MFEX is to take advantage of the opportunity to be carried by the Mars Environmental Survey (MESUR) Pathfinder mission to the surface of Mars, where it will perform technology, science and MESUR mission engineering experiments.

MESUR MISSION BACKGROUND

The MESUR concept was an extension by the Ames Research Center of a mission set envisioned to place a network of meteorology and seismology stations on the surface of Mars. These missions were to extend the results of Mars Observer to continue to global characterization of Mars, The uniqueness of the MESUR concept was that the landers would go directly from the earth to Mars, enter the atmosphere and land without an orbiter.

The MESUR Pre-Project was transferred to JPL in 1992, where it was divided into two activities, Pathfinder and Network. Because the concept of a direct earth-Mars mission is new, and because the capital investment in a multi-lander MESUR Network is large, MESUR Pathfinder was conceived as a technology demonstration, MESUR Pathfinder is planned to be started by NASA 0SS (Office of Space Science) in FY94 and is cost-capped at $150M in FY92$ for Phase C/D as the first in the Discovery series of low-cost planetary missions, MESUR Pathfinder will launch in November or December 1996, with a single spacecraft which will fly directly to Mars, enter the atmosphere with a Viking-derived heat shield, and land with the aid of parachutes and airbags. Landing will occur in November or July 1997, depending on the choice of trajectory.

The MESUR Pathfinder experiments are primarily engineering (atmospheric measurements during entry, assessment of parachute and airbag performance, etc.) However, for science Pathfinder will include a stereo camera system (to be provided by the University of Arizona) which will provide a panorama of the Martian surface, thus increasing the small scale knowledge of Mars by 50% over the two Viking sites. Pathfinder will also make temperature and pressure measurements at the site,

Other important science measurements desired for Pathfinder are to identify the elemental composition of rocks and soil, and to measure the seismic background of Mars for designing seismometers for the Network mission, The Max Planck institute of Germany, aided by the University of Chicago, is providing an Alpha Proton X-Ray spectrometer for the composition measurements. A small rover is a desirable means of instrument deployment since it provides a high likelihood of being able to reach rocks in the vicinity of the lander. The rover can also deploy other instruments, provided they are small enough,

However, a question exists, given the uncertainties in the Martian soil and terrain characteristics, of a small rover's ability to move about competently enough to perform these tasks. NASA OACT has funded rover research for many years, Therefore OACT agreed to provide a rover to MESUR Pathfinder as a proof of concept of small rover capabilities, and as a mechanism for technology transfer to MESUR Network and following missions. MESUR MFEX is cost-capped at $25M in real year dollars for Phase A through operations, and is not included in the $150M MESUR Pathfinder costs.

The primary requirement of the MFEX is to accomplish its objectives within the $25M cost cap, The second most important requirement is that the rover must not cause MESUR Pathfinder to exceed its cost cap. The first requirement led to the selection of the basic Rocky 4 design as the starting point for MFEX rover design. This features 6 powered wheels attached by a set of “bogie levers” to a single body. The front and rear wheels are steered via Ackerman steering (like an automobile). Control is shared between earth (operator target designation based on stereo images sent from Mars) and the rover (autonomous “behavior” control using on-board sensing for path following and hazard avoidance).

While other designs (e.g. legs, on-board target selection, etc) may eventually prove superior, the years of experience with, and approximately $3M of investment in the Rocky series, combined with the the time and cost constraints of MESUR Pathfinder, prohibit the consideration of other, less developed concepts. The information gained from MESUR Pathfinder will allow selection of the optimal concept for future Mars rovers for Network, Sample Return, etc.

The “Rocky” based design is described below in more detail, including decisions made to minimize the impact of the rover on the MESUR Pathfinder mission cost,

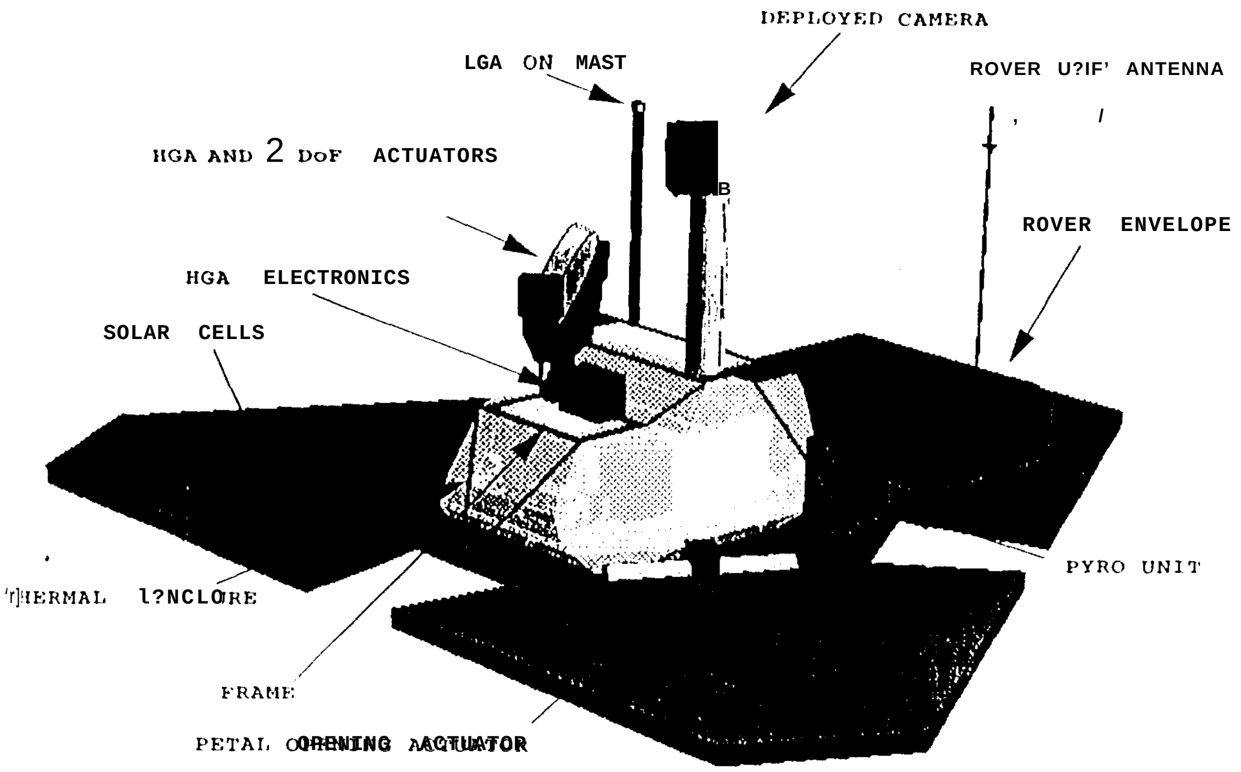
MESUR PATHFINDER MISSION DESCRIPTION

MESUR Pathfinder will be launched on a Delta. The rover will be mounted on one of three panels in the tetrahedral lander and tied down with a separation connector. During cruise (launch through landing) the rover will be provided structural and thermal support and limited data collection/transmission by the lander/cruise stage. The entry and landing are planned to minimize g-levels on the payload to <50 g’s with the combination of parachutes and airbags, so the rover will be qualified to 100 g’s. After impact the lander will open (see Figure 1), positioning the panels so that solar energy can be collected and the rover is poised for deployment.

The lander will immediately transmit the engineering data collected during the descent. Then its camera will take a panoramic image of the surroundings and begin transmitting it directly to the earth at a few hundred bits per second. (MESUR Pathfinder has no orbiter, and Mars Observer cannot be relied on as a communication relay). The initial portion of the panorama to be transmitted will be in front of and behind the rover panel to allow the choice of rover deployment direction and initial operations to be made.

Figure 1.

MESUR PATHFINDER DEPLOYED CONFIGURATION



The rover will be deployed from its attach point on the lander. Since the lander is volume constrained, the rover will be carried in a stowed configuration with the body lowered, and will erect itself after release and before deployment. The rover will move down deployment ramps to the surface, and will thereafter be independent except for using the lander data and communications functions for command and telemetry. After rover deployment and transmission of the panorama, much of the lander mission is focussed on supporting the rover with imaging, telecommunications, and data storage.

ROVER MISSION OBJECTIVES

The rover has three primary mission objectives:

1. Technology Experiments
2. Science Experiments
3. Mission Experiments

The rover is a NASA OACT flight experiment for autonomous mobile vehicle technologies, whose prime function is to determine microrover performance in the poorly understood Martian terrain, The primary means of collecting this technology information is by instrumenting the rover mechanisms to determine wheel-soil interactions, detect hazards, determine navigational errors, etc.

Because the rover is part of the MESUR Pathfinder payload it will also gather science data by deploying an alpha-proton-x-ray spectrometer against one or more rocks, and possibly soil.

Finally, because MESUR Pathfinder is an engineering test of a transport and landing system for Network, the rover will image the lander to allow its condition to be assessed.

Technology Experiments

The MFEX is primarily a technology experiment to determine microrover performance in the poorly understood Martian terrain such that future rovers can be designed to be effective in navigating and moving over the surface of Mars,

The technology experiments to be performed by the rover were selected by two workshops in the fall of 1992 and the spring of 1993. The workshop participants were from NASA centers, universities, industry and other countries (France and Russia). At the first workshop experiment objectives were defined and experiment concepts were developed, Experiment concepts were fleshed out and presented at the second workshop and the final set was selected.

The selected technology experiments are listed in Table 1, They were chosen to meet the most important objectives within the constraints of the MFEX mission. The microrover will conduct the experiments and telemeter experiment data to the lander for return to earth, in order to enable the mobility, controllability, and robustness of the microrover design in the Mars surface environment to be assessed and to provide data for the design of future Mars rovers.

TABLE 1
PRIORITIZED TECHNOLOGY EXPERIMENTS

1. Terrain Geometry Reconstruction from Lander/Rover Imagery
2, Basic Soil Mechanics
3. Dead Reckoning Sensor Performance and Path Reconstruction/Recovery
4. Sinkage in Each Soil Type
5. Logging/Trending of Vehicle Performance Data
6. Rover Thermal Characterization
7. Rover Vision Sensor Performance
8. UHF Link Effectiveness
9. Material Abrasion
10. Material Adherence

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11. Rock Hardness (To be performed if feasible within cost/capability constraints.)

1. <u>Mars Terrain Geometrv Reconstruction from Imagery</u> - Lander and rover imagery will be analyzed on the ground to determine terrain feature classes (soils, rocks, hills, etc) as well as statistical size and location distributions.

2. <u>Mars Basic Soil Mechanics</u> - Ground analysis of rover telemetry will be used to determine basic Martian soil mechanics parameters needed for future Mars rover design, such as cohesion, internal friction angle, slippage, and drive resistance. The rover will be instrumented to provide relevant telemetry such as motor currents, wheel and steering motor encoders, bogie angle encoders, etc.

3. <u>Mars Dead Reckoning Sensor Performance and Path Reconstruction/ Recovery</u> - Position errors on Mars arising from using dead reckoning (internal state) sensors to control mobility will be measured, including 3-axis accelerometers and a heading gyro. Uncertainties will be characterized as a function of distance over various Martian terrain types determined from the lander and rover imagery. It will also be determined if the dead-reckoning system can recognize terrain types by observing vehicle behavior, for example, by traversing a closed or open path, noting vehicle behavior through engineering telemetry, and noting differences between the lander and/or rover imaged position and that position output

from the dead reckoning system. Also, visual sensing of terrain types will be correlated with the behavior of the vehicle measured from telemetry and an array of several proximity sensors mounted on the rover.

4. <u>Sinkage in Each Martian soil Type</u> - Wheel tracks will be viewed with the rover camera or proximity sensors to estimate sinkage. In particular, the rover will lock 5 wheels and rotate the sixth, measuring the motor current as the wheel breaks free, and then imaging the hole left by the rotated wheel. For experiments done close to the lander the lander camera may be used to image the wheel tracks, A goal is for the lander camera to image the total trail left by the rover during its mission,

5. <u>Logging/Trending of Vehicle Performance Data on Mars</u> - All measurable engineering parameters (drive torques/current, rpm, voltage, etc) will be logged and time tagged. Terrestrial analysis of the logged data will determine performance, degradation, etc. This data will also be used to determine the values in Basic Soil Mechanics, above.

6. <u>Rover Thermal Characterization</u> - Rover thermal behavior as a function of time and operating situation will be monitored by thermal sensors in the wheels and some of the sensors, and inside the Warm Electronics Box (see below for a description of the WEB). The data will be analyzed on the ground to characterize rover thermal behavior.

7. <u>Rover Imaging Sensor Performance</u> - Terrain, motion and track measurements derived from the rover imaging sensors will be correlated with direct measurements from proximity sensors and engineering instrumentation,

8. <u>UHF Link Effectiveness</u> - This experiment will determine whether the UHF Link will function effectively on Mars by observing signal strength and noise as a function of distance between the rover and lander, and/or when the rover is occluded by terrain features, This measurement will be made by tracking the number of retransmissions required between the rover and the lander.

9. <u>Material Abrasion</u> - The abrasive qualities of Martian soil and dust will be measured, The proposed measurement involves painting one wheel with a fluorescent paint, covering it with an opaque paint, and observing the

wheel with a photocell to see when the outer paint wears away, revealing the fluorescent paint. Lewis Research Center is providing this experiment.

10. Material Adherence - The tendency of Martian dust to adhere to rover surfaces, especially solar arrays and detectors, will be observed, Lewis Research Center has designed a simple experiment to periodically uncover a reference solar cell to determine the difference in power between the clean reference cell and a (possibly) dusty cell. The experiment also uses a quartz microbalance to determine the mass of the dust.

11. Rock Hardness (if feasible) - Rock hardness is of interest for correlating the materials abrasion experiment, and for shedding light on the design of material sampling technology for future missions, However, the constraints of the rover prohibit it from carrying a rock chipping or coring tool. A concept has been proffered for the rover to “claw” at a rock with one of its wheels, using the wheel grousers or an abrasive strip to erode the rock face, however, implementation of this concept awaits testing of the rover capabilities,

The mission design allows at least one instance of each of the technology experiments to be accomplished within the first three days of surface operations. Soil characterization experiments will be conducted in at least three soil types, provided three soil types are within range of the rover at the landing site.

Science Experiments

Although the information gained from the rover technology experiments (soil mechanics, materials adherence, etc.) are of scientific interest, the rover's main science objectives are to deploy the APXS and take close-up images of Martian features,

1, APXS - The primary science objective is to place the alpha-proton-x-ray spectrometer (APXS) against a rock, collect a spectrum, and transmit the spectrum to the lander for return to earth. A full APXS measurement of a rock requires 10 hours. The 10 hours of measurement need not be contiguous but the rover must keep the APXS fixed on the rock until 10 hours of data is obtained, As a goal, if surface geometry and time permit, the rover will place the APXS on a rock particularly designated by the science team. However, if terrain conditions prevent the best rock from being contacted early in the surface operations, the rover will measure any rock it encounters.

An APXS deployment mechanism is currently being designed, It appears most likely to be located on the back of the rover where real estate is available without interfering with the hazard detection sensors. If feasible, this mechanism will allow the rover to collect soil measurements, However, a rock measurement has priority over a soil measurement. As a goal, if time permits and the APXS has the appropriate deployment mechanism, APXS measurements of three different soil types will be made.

2.' Imaging - The microrover will take a close up image of any rock of which an APXS spectrum is obtained and transmit the image to the lander for return to earth. The image will be black and white and monoscopic but will be intended to show structure at higher resolution than obtainable by the lander camera. The rover computer is capable of compressing and storing a single image on-board. Imaging of rocks may be done by turning around and using the front cameras, or a rear-mounted camera may be included as part of the APXS deployment mechanism.

3. Other Science Objectives - The rover may be asked to carry other science instruments, i.e. a neutron spectrometer, and may be asked to assist in the deployment of a seismometer. The ability of the rover to carry out these tasks depends on the mass, power and configuration of the instruments. Design trades are currently being made to determine whether the experiments are affordable by MESUR Pathfinder, and whether their design can meet the rover capabilities.

Mission Experiments

Because MESUR Pathfinder is primarily an engineering demonstration, assessment of the lander's condition is very important, The microrover will image the MESUR Pathfinder lander at least once to assess its condition after landing, and will transmit the image(s) to the lander for return to earth. The microrover's image(s) of the MESUR Pathfinder lander will be black and white, monoscopic, and will encompass the entire lander cross section.

As a goal, the rover will acquire three images of the lander from three rover vantage points spaced at 120° apart around the lander, If necessary, the nominal mission could be revised to allow the rover to take close-ups (stereo, if necessary) of damaged areas on the lander,

ROVER MISSION DESIGN

Because of cost constraints, both the lander and the rover have limited redundancy. In addition, the thermal environment of the Martian surface is very harsh (cycling between about O to -1 OO°C daily). Therefore the surface mission design is focussed on achieving the important mission objectives in a relatively short time.

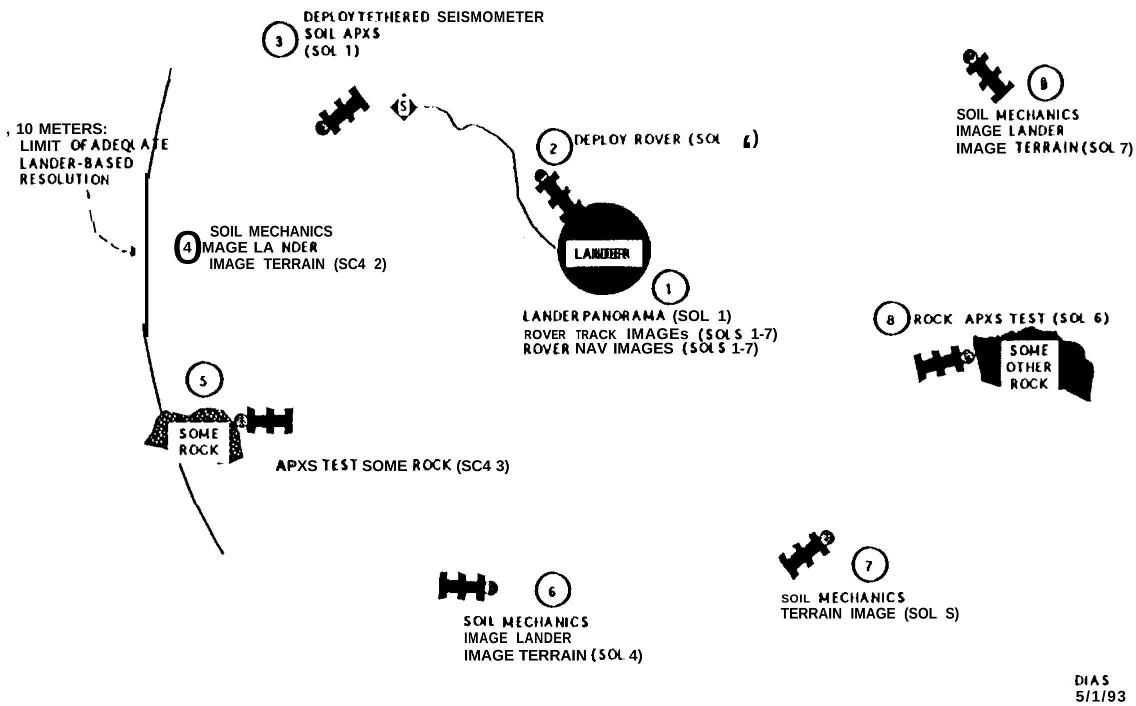
The mission design is severely constrained by the lander-to-earth direct communications link (limited to a few hundred bits per second, even using a lander high gain antenna), The landing site only faces earth for 12 hours per day or less. The lander is solar powered (RTG's being prohibitively expensive) and therefore transmits mostly during daylight hours, although it does have rechargeable batteries. However, transmission power is so high that the lander's batteries are excessively drained by more than a few hours of transmission per day.

The rover navigation scheme involves the earth operators selecting a target and "way-points" on the way to the target, and uplinking the way-point designations and commands for tasks on the way to the target. Because of telecommunication limitations the rover can only be commanded once per day, Since terrain conditions can only be inferred from the lander images operators will be reluctant to initially send the rover on traverses of more than a ten or so meters per day, All of this means that the surface operations must be designed to be very efficient in accomplishing objectives.

The tool for surface mission design is scenario development, with timelines built around data transmission capabilities. A cartoon of an example scenario is shown in Figure 2. Here, the rover is deployed on the first day (or "sol", a Martian day which is nearly the length of an earth day). The cartoon shows that the rover's first activity is to deploy a seismometer. However, this now appears likely to be too heavy for the rover to carry. Next, the rover is directed toward a target rock, pausing to perform soil mechanics experiments and image the lander.

Figure 2

MESUR PATHFINDER ROVER
NOMINAL 525 BPS 7-sol SCENARIO, 15°s



This scenario assumes that the rover gets near the target rock on the first sol. The next sol is consumed directing the rover to contact the rock and place the APXS on it. Cost constraints make it unlikely that the rover will be able to autonomously reach the rock and place the APXS on it with only one earth command. This, plus the probability of navigation errors (e.g. wheel slip preventing accurate dead reckoning) have led to a scheme where the rover position will be determined relative to the target at the end of each sol by imaging it from the lander, The APXS spectrum in this scenario is taken overnight, to conserve the daylight hours for rover movement. The overnight spectrum will be powered by the rover's batteries, An APXS soil measurement may be taken first to increase the probability that some key science data will be returned, even if the rover or lander "die" early,

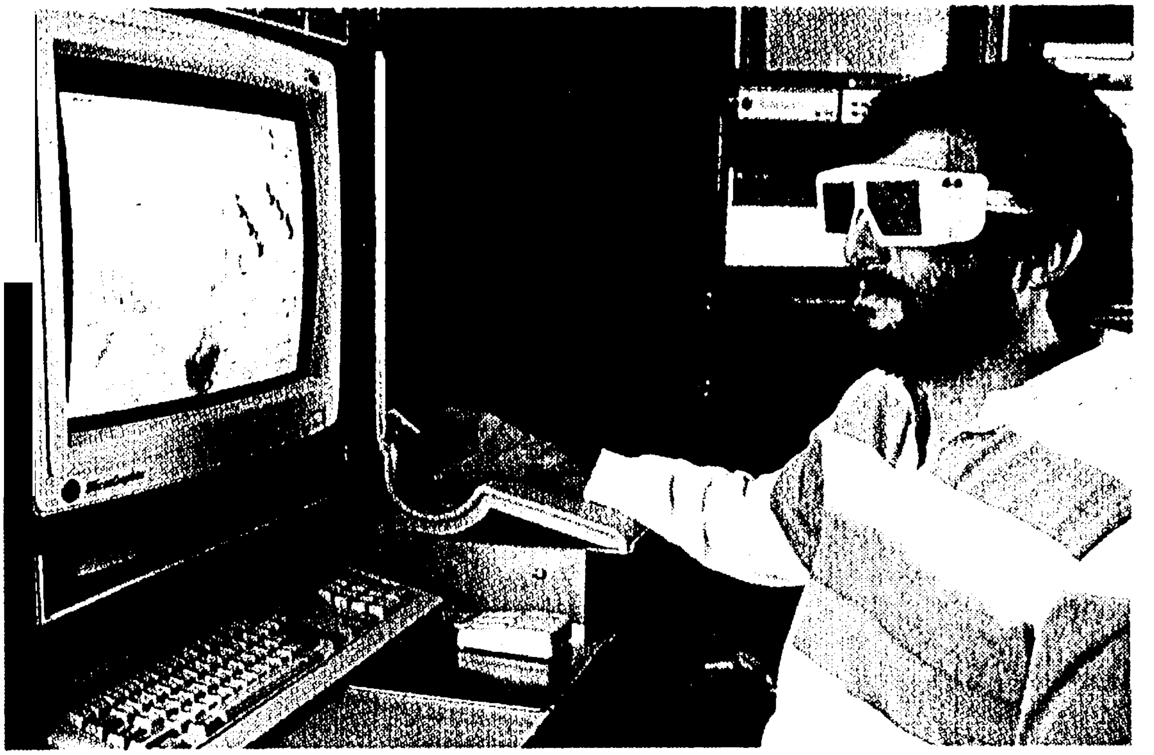
Having accomplished its most important objectives in the first three sols or so, the rover is directed around the lander, conducting technology experiments in different soil types, imaging the lander from other vantage points, and collecting APXS data from another rock, By the end of the seventh or eight day of operations the full lander panorama has been . transmitted, the primary rover experiments accomplished, and the extended mission phase begins. The prime mission is envisioned to be accomplished within 10 meters of the lander to take advantage of the highest resolution lander images. For the extended mission the rover can be risked on longer traverses. It can even head "over the horizon" (out of range of the lander's camera) by using its own images for navigation.

The scenario describe above is an example. A number of alternative scenarios will be constructed before the landing to account for differences in circumstances: non-nominal landings, problems with panel deployment, unexpectedly rough (or reckless) terrain, etc.

ROVER OPERATIONS DESIGN

The rover is controlled by an earth operator who views a work station with a stereo display of the lander's image of the terrain through 3-D glasses. Figure 3, from Reference 11, shows this arrangement. The work station's software allows an icon of the rover to be placed in the scene and the coordinates of this placement determined. These coordinates form the basis of the rover traverse commands. Commands which enable rover tasks, e.g. "perform a soil mechanics experiment", "place the APXS on a rock", are interspersed with traverse commands and sent to the rover through the MESUR Pathfinder Mission Operations System (MOS). The commands are sent shortly after sun and earth rise on Mars, and are received by the lander. The lander stores them until notified by the rover that it is awake and ready to receive its commands. The lander forwards the commands to the rover over the lander-rover UHF link, and the rover

Figure 3. Operator Work Station for Rover Control



stores them for execution.

Because the rover reacts to Martian terrain conditions the times of traverse and experiment execution are non-deterministic. Therefore, the rover activities are commanded asynchronously in contrast with normal spacecraft sequences. "Time-out" limits will be provided for each function so that if, for example, a destination is not reached within a pre-specified time, the rover will cease trying and continue with the next planned activity or "call home" for further direction.

Rover telemetry, including images, is stored, compressed and packetized on the rover. The rover notifies the lander when it is ready to transmit, and the lander o.k.'s transmission when it is ready to receive. Telemetry packets are downlinked over the rover-to-lander UHF link and the lander stores the packets for transmission to earth. The lander is not required to process either rover command or telemetry packets, other than to read the packet headers and transmit the packets. This greatly simplifies the rover/lander interface and is a cost savings on both sides,

On the earth, the rover images and engineering telemetry can be displayed on the operator workstation and/or sent to auxiliary workstations for analysis.

The total cycle for rover (and lander) commanding is designed to be done overnight, That is, from the time the lander images of the rover and the rover telemetry are received at the end of the sol's Mars operations, to the time the next sol's commands are transmitted is about twelve hours. In the absence of anomalies this timeline is feasible provided that review and approval is minimized. Experience shows that designating the rover path and selecting the tasks to enable only requires a few minutes, Since the rover and lander commanding is relatively independent and asynchronous, interleaving of commands and contention for resources is minimized.

The highest risk area, in terms of timing, is the first sol after landing, The landing will occur in the morning and the ground operators must react to the first lander image within two hours to allow rover deployment on the first sol. That is, the representatives of technology experiments, science and lander health assessment must be prepared to select targets and activities with little contention. The development of operations team structures to minimize the number of decision makers and approvers is a challenge.

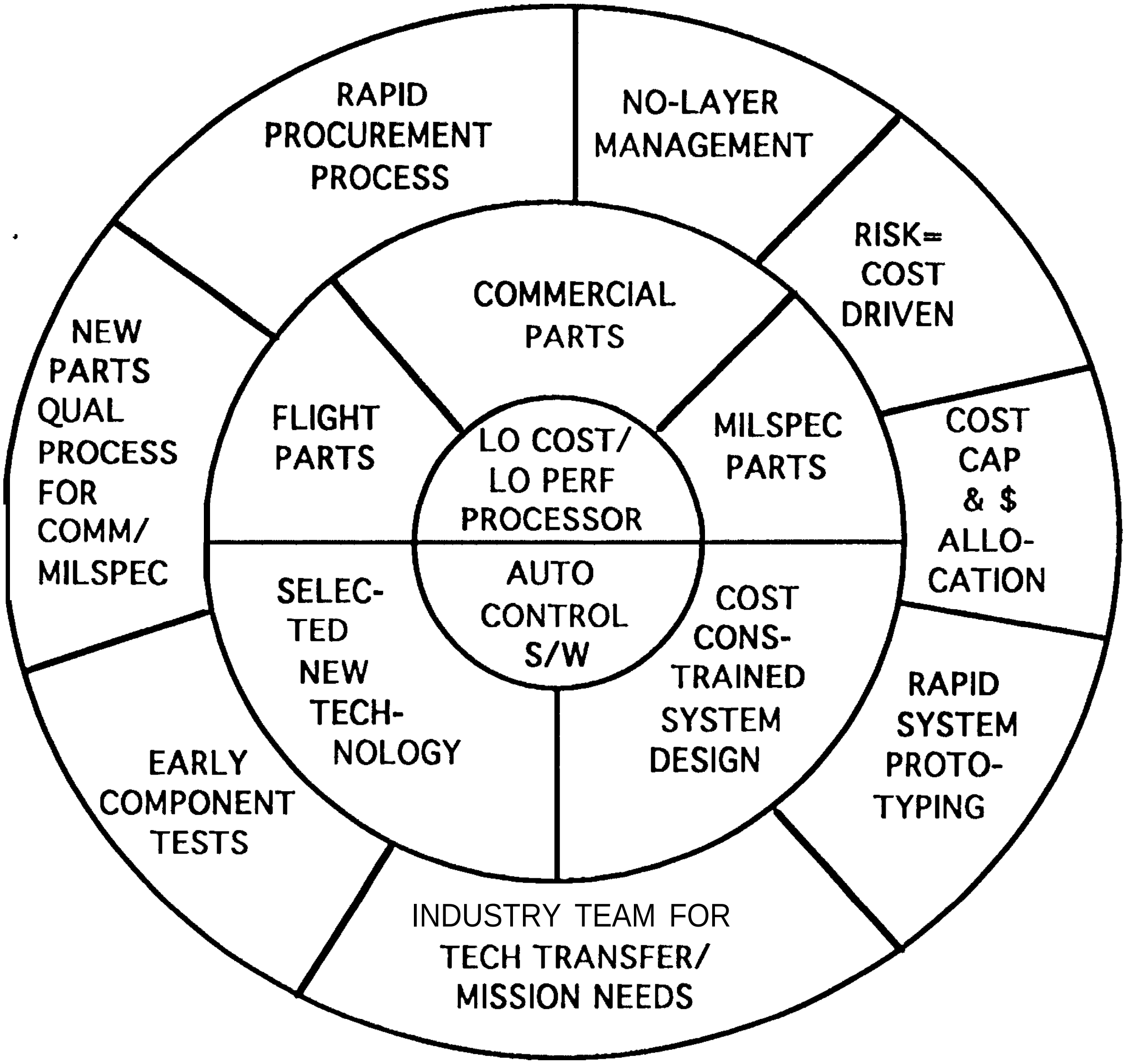
As part of the low-cost process for MESUR Pathfinder the End-to-End Information System (EEIS) is being developed using a concurrent engineering process, The rover operations development is an intimate part of this process and is the focus of the earliest design and test activities.

ROVER DESIGN

Design Philosophy

MFEX is an example of a "Better, Faster, Cheaper" NASA activity, Consequently its design and new processes are being developed concurrently, as illustrated in Figure 4. The focus of the cost constrained activity is a deliberate constraint on computational power, coupled with new autonomous control software technology and sensing/control architecture. Performance and risk are variables to achieve the costs constraints (for example, low-speed computing is enabled by slow rover speeds).

FIGURE 4. ROVER DESIGN PHILOSOPHY

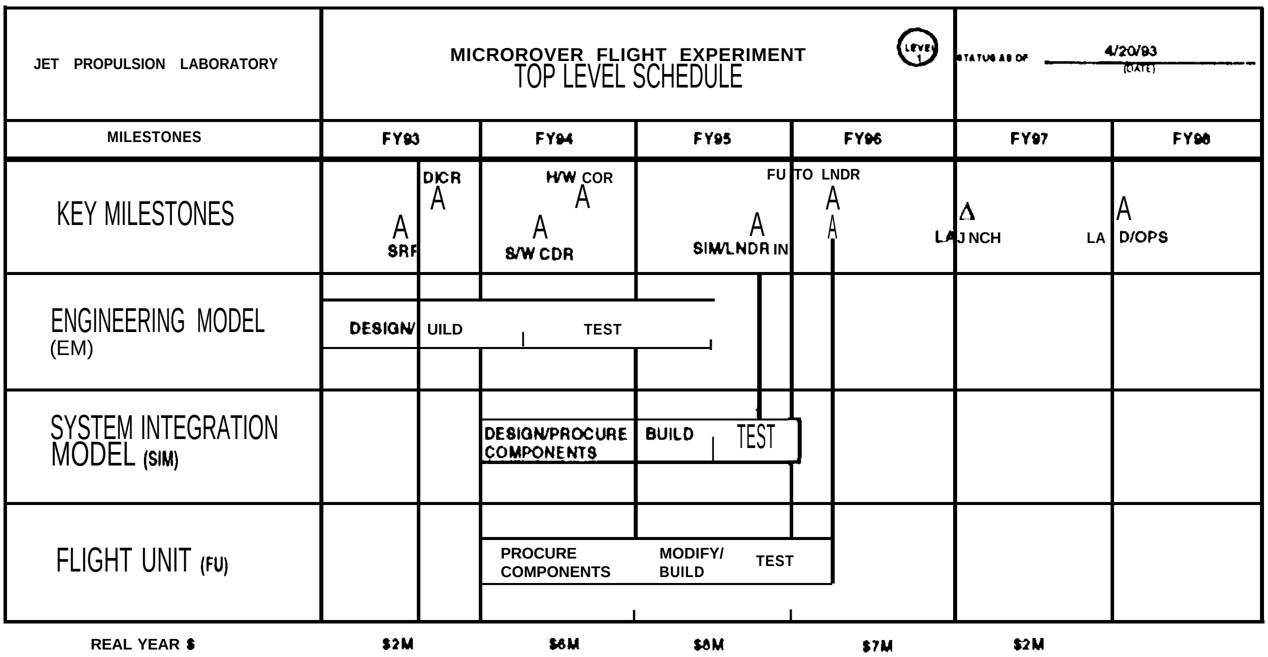


The selection of affordable parts and a cost-constrained design are built around the low performance core. Around that are wrapped cost effective processes: a small, low overhead team; rapid prototyping/concurrent engineering; selected industrial participation for cost-effective technology transfer; new processes for parts qualification and procurement; etc.

Although only in Phase A, MFEX is currently on schedule and within budget. A top level schedule, with the projected funding profile, is shown in Figure 5.

The NASA Office of Safety and Mission Quality (Code Q) has selected MFEX as an example of a “Class D“ project and MFEX is documenting its risk mitigation processes and their results to be used in the formulation of future standards for such projects, New processes for parts qualification, procurement, and program control are being developed by JPL with an MFEX focus.

Figure 5.



The rover design is governed by the $25M cost constraint, Costs were allocated to system and subsystems, including operations, before the design was selected. The initial design exceeded the cost constraints, so it was descoped. For example, extra test hardware was removed and mission performance was lowered.

The rover design is also limited by the need to minimally impact the lander. Consequently, the rover mass and volume are limited, and the rover is "free-ranging", utilizing a UHF link for communication even during cruise, to minimize the interfaces with the lander,

In order to meet the cost constraints the rover will take selected design risks. One of these is to maximize the use of off-the-shelf commercial and Mil-standard parts, This is enabled by the fact that the mission duration is relatively short, and that the radiation environment is relatively benign. New classification and qualification procedures are being developed at JPL to minimize the cost of using such parts. Class S flight qualified parts are used where ever cost effective, e.g. the CPU is Class S. Figure 6 is a matrix of parts type vs flight readiness.

Another risk is the limitation on redundancy, The rover design is as failure resistant as possible within the cost and mass constraints. Block redundancy is practically nonexistent, but considerable functional redundancy is used, e.g. solar panels and primary batteries.

Test Philosophy

The design makes maximal use of the "Rocky" series heritage, but includes several features that were not necessary for the previous ground demonstrations. Table 2 illustrates some of these differences.
The MFEX activities are built around a rapid prototyping approach. "Rocky 4" was stripped to the bare chassis for mobility testing (Rocky 4,1), Motors and mechanisms closer to flight were added and the chassis was given to the control subsystem, Control breadboarded a complete suite of sensors and a processor and 1/0 board, for use in software development (Rocky 4.2 is now operating in the sandbox). The next step is to replace the breadboard components with more flightlike "brassboard" components to allow the software to be tuned for flightlike operations, including integration in the MESUR EEIS development (Rocky 4.3).

Figure 6.

MICROROVER TECHNOLOGY MIX

ACTIONS

TECHNOLOGY LEVEL	USE AS-IS	MODIFY	QUALIFY	DEVELOP
COMMERCIAL	• 80C85 s/w DEVELOPMENT ENVIRONMENT • SOME MOBILITY COMPONENTS	• THERMAL-VACUUM ENCLOSURE • SOME MOBILITY COMPONENTS • PROXIMITY SENSING H/W	• SOME MOBILITY COMPONENTS	
MIL-SPEC	. UHF MODEMS • POWER CONVERTERS			
FLIGHT QUALIFIED	• 80C85 CPU • SOLAR CELLS • BATTERIES			
NEW TECHNOLOGY			• MOBILITY CONCEPT • SYSTEM CONCEPT	• CONTROL S/W • I/O BOARD • PROXIMITY SENSING S/W • SOME MOBILITY COMPONENTS

In parallel with this system development, component selection and testing are proceeding. For example, commercial motors and gears are being evaluated in a small thermal-vacuum chamber for their resistance to frigid Martian conditions.

These rapid prototyping activities have been facilitated by a new rapid procurement process developed by JPL's procurement organization to support the "Better, Faster, Cheaper" way of doing business.

The next step in the rapid prototyping process is to procure two sets of flight hardware, storing one set in clean conditions and using the other set to construct a "System Integration Model" or SIM. The SIM will be subjected to field and environmental testing, and will be used to do interface checks with the MESU R Pathfinder spacecraft during its

Table 2
Rocky 4 Demonstration vs Flight Rover Characteristics

	ROCKY 4 DEMO	FLIGHT ROVER
SYSTEM		
SIZE	60 X 46 X28 CM	SAME
MASS	7 KG	SAME
PERFORMANCE	TAiLORED DEMO	ROBUST
QUALIFICATION	NONE	FLIGHT QUAL
ENVIRONMENT	BENIGN	HARSH
COMMAND CYCLES	MANY	1 PER DAY
BUDGET/SCHEDULE	TIGHT	TIGHT
SUBSYSTEM		
CHASSIS	FIXED	STOWABLE
MECHANISMS	RADIO SHACK	MIL-SPEC
COMPUTER	WIRE WRAP	CLASS S
S/W	HACK	FLIGHT QUAL
THERMAL	NONE	WARM BOX, HEATERS
POWER	COMMERCIAL BATTERIES	SOLAR ARRAYS, FLIGHT BATTERIES

Assembly, Test and Launch Operations (ATLO). Based on the SIM results the Flight Unit will be built up, perhaps with some parts modifications, in clean room conditions. This is more arduous than normal spacecraft cleanliness because of planetary protection restrictions,

The Flight Unit will be integrated with the flight spacecraft and will be subjected to flight environmental testing in conjunction with the spacecraft,

Rover Design Description

The MFEX rover configuration is shown in Figures 7, 8 and 9. The rover, including its mounting and deployment equipment, is constrained to mass less than 14 kg, The rover has an anticipated mobile mass of 9.0 kg, without science instruments. Another 5.0 kg is allocated for lander-mounted rover telecommunications equipment, structural support of the rover and its deployment mechanisms, (The MESUR lander mass is limited by the relations between ballistic coefficient, g-loading of airbag impacts and parachute size. Significant launch mass margin exists.) Volume is constrained by the folded lander's tetrahedral shape The rover competes for space with the lander thermal enclosure, parachutes and other systems. While the rover has a nominal height of 280 mm (with 130 mm ground clearance), the available lander volume allows only 200 mm, forcing the rover to stow at a static height of 180 mm (see Figure 10), The rover is 630 mm long by 480 mm wide,

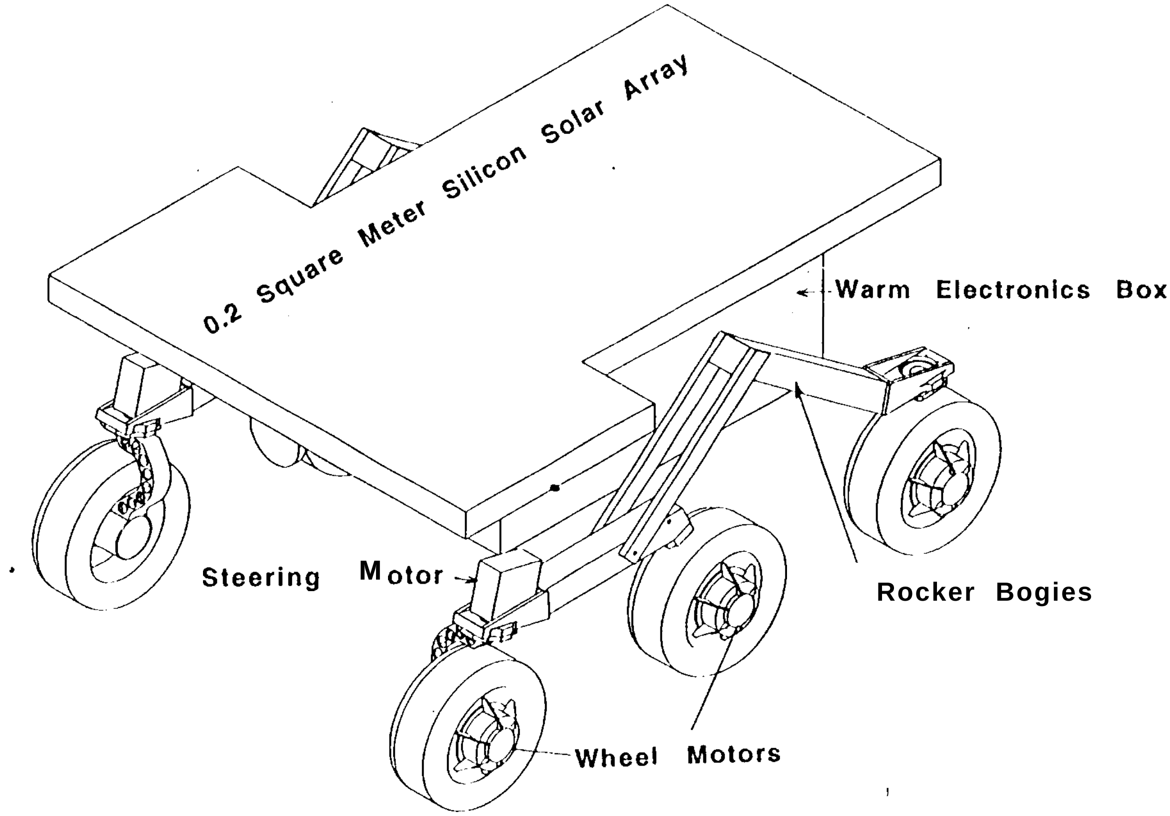
This small size poses considerable challenges for mobility, computation, thermal control, telecommunications, and power.

Mobility/Structure/Mechanisms

The rocker-bogie mobility system was developed over several years using custom computer models developed at JPL, as well as analysis tools such as NASTRAN (FEM) and ADAMS (dynamics code), verified through the development of scale physical models. When overcoming obstacles, the lever arms of the suspension reduce the incline angle of the master rocker, The single body is mounted to the rocker through a differential, cutting the incline angle in half again. This results in a very stable platform (when compared to more conventional three body designs) for science, imaging and proximity sensing. The vehicle is steered with its four outer wheels, allowing it to turn in place, or to Ackerman steer (like an automobile) about a point outside the vehicle.

In the past few months mobility was tested in a tilting sandbox filled with dry sand and then with lunar simulant. The 130 mm diameter wheels were widened to 60 mm contact to reduce ground pressure and therefore limit sinkage in loose soils such as are expected on Mars. Sandbox testing was done with a stripped chassis to simulate performance at the 3/8 g Martian gravity. The results were that the system could climb slopes of 32° in dry sand (within 2° of the angle of repose, which is the maximum slope at which loosely deposited material will be stable), and 17° in lunar simulant. Additional testing may be performed in dry clay material, if resources permit, which is believed to be a better simulant of Martian

Figure 7. Rover Configuration



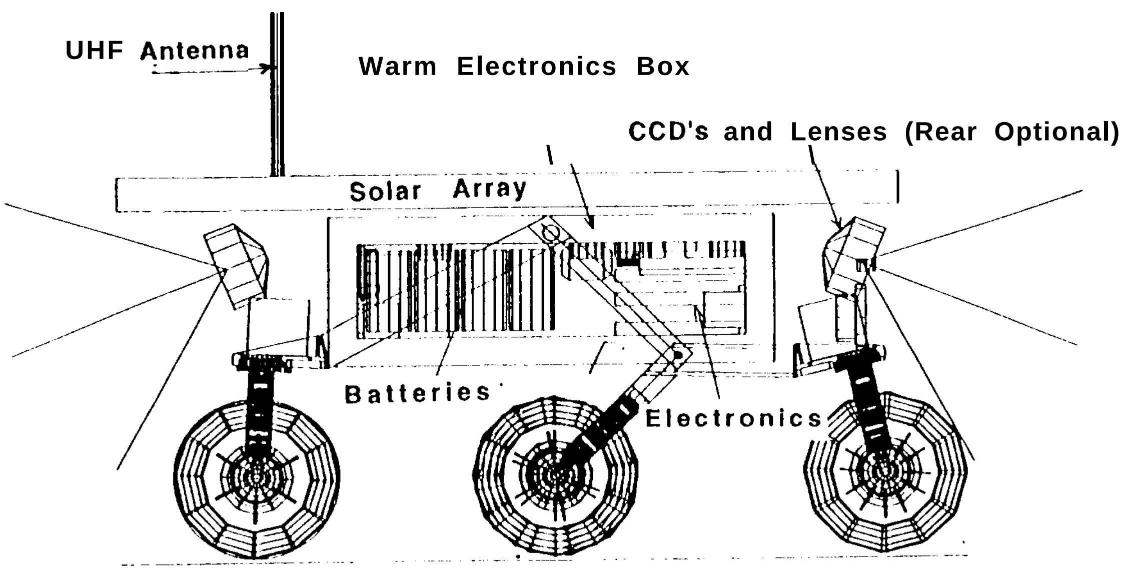


Figure 8. Rover Configuration Side View

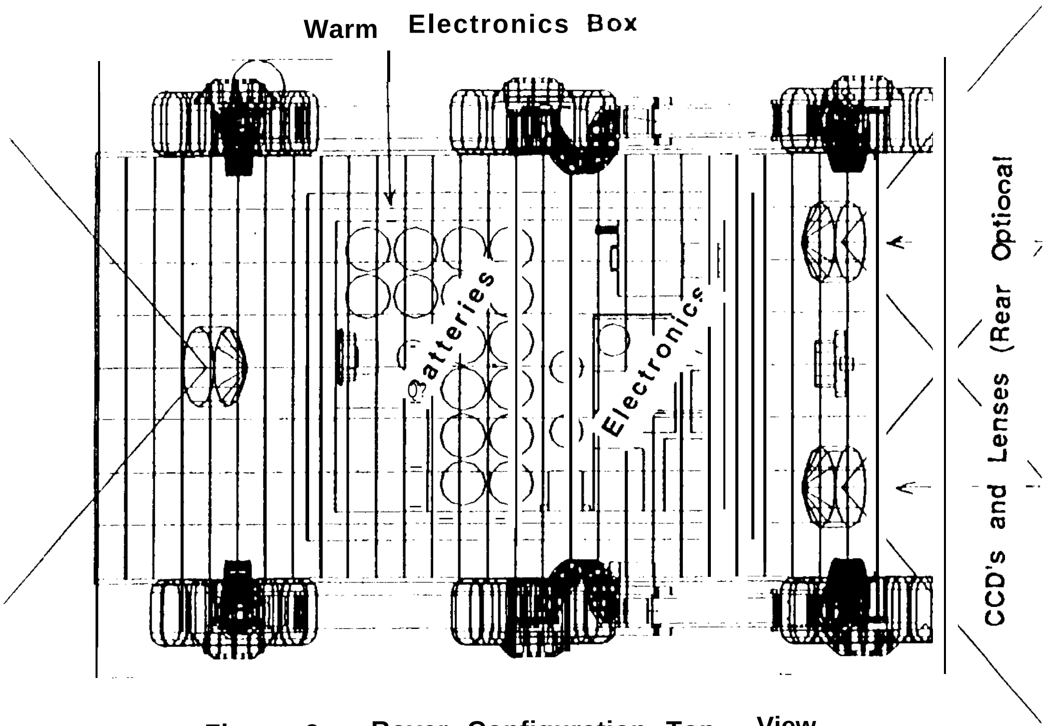


Figure 9. Rover Configuration Top View

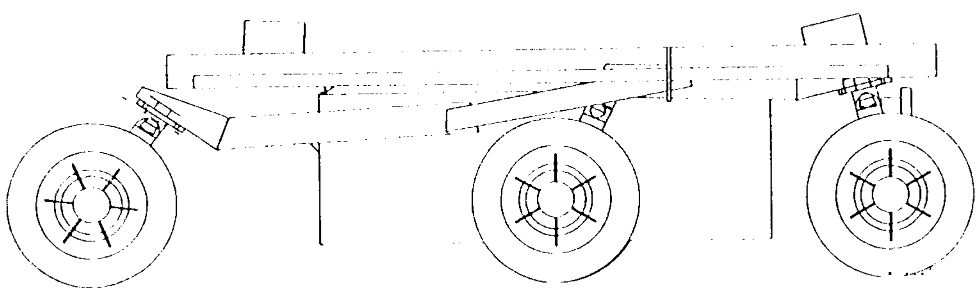


Figure 10. Stowed Configuration

soil. The results of the tests demonstrated some difficulty with repeatability, which is not unusual in soil mechanics experiments. But they do indicate that the Rocky configuration is likely to function adequately on Mars to acquire the necessary terrain data, provided sufficient soil mechanics experiments can be done.

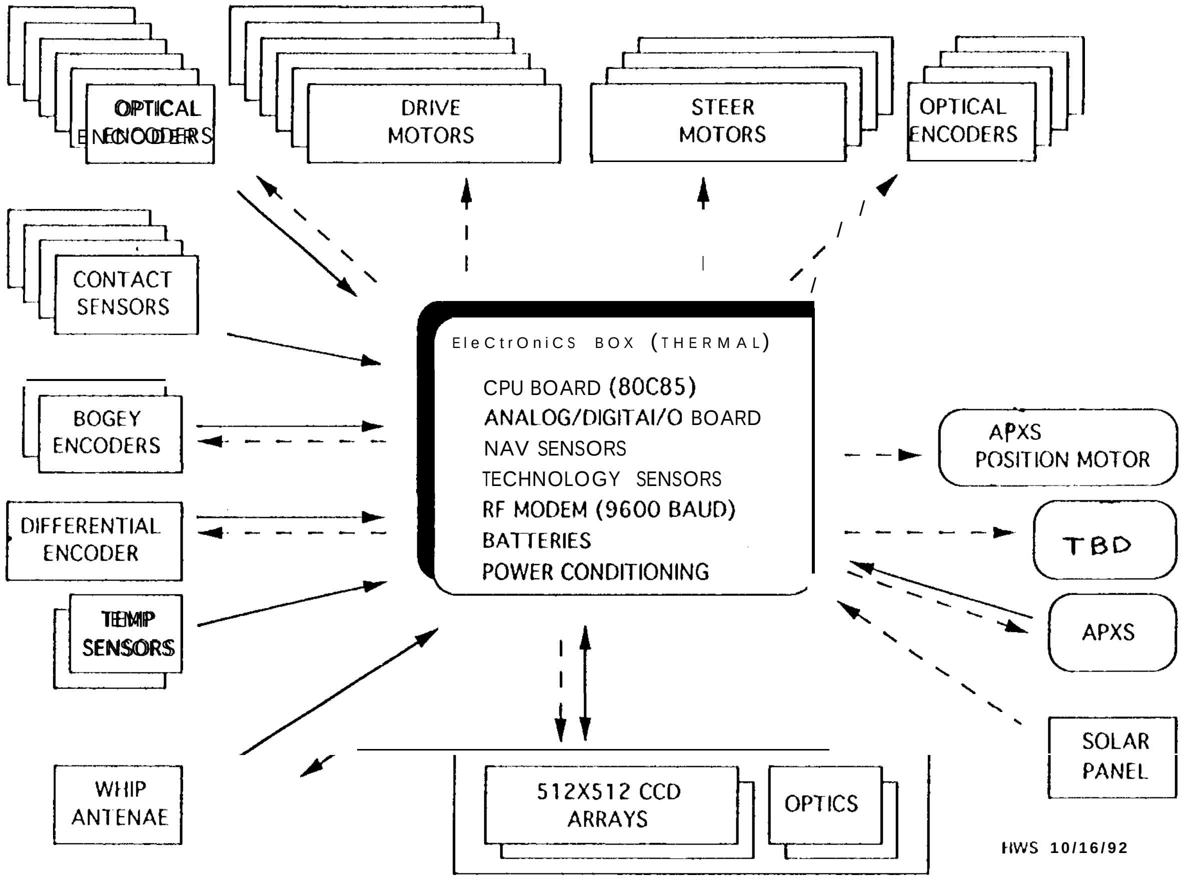
The Rocky 4 structure was severely lightened to achieve the desired 7 kg. This resulted in some problems with insufficient stiffness which could affect the navigation sensing, and the MFEX rover structure is likely to be somewhat heavier to handle these stiffness concerns as well as landing loads.

Component selection and qualification is proceeding in parallel with system testing. Maxon rare earth motors have been selected for propulsion and steering, Mobility sensors have been designed and parts selected for testing, Gears with plastic bearings are being tested with different types of lubricants at low temperatures and pressures. Wear does not seem to be a problem, but viscosity is undesirably high at the present time, The use of commercial parts is enabled in part by the slow design speeds of rover mobility (<2 cm per second). Simplifications in the mobility approach have been taken to minimize power and control subsystem costs. For example, the motors are powered through a "bang-bang" control system rather than through proportional speed control.

Control

As described earlier, the rover control system features operator designation of targets and autonomous control to reach the targets and perform the tasks. The on-board control system (shown conceptually in Figure 11) is built around an Intel 80C85 processor, selected for its low cost and Class S radiation/Single Event Upset resistance, This is only an 8-bit processor which runs at about 100 kips, in contrast to new technology flight processors. However, development to date indicates that it is ample for the rover's needs, provided that rover speeds remain slow. (Note that it is also vastly superior to all the computers used by planetary spacecraft before Galileo). A commercial version of the 80C85 was acquired inexpensively for system and software development, and flight parts are also available at JPL in the form of Cassini spares available for purchase by the rover.

Figure 11. Control Schematic



An I/O board is being constructed which can be cheaply manufactured in Class S technology, and in a small, low power package. The processor and 1/0 board package form a computer which will perform all the computational functions of the rover, from command decoding, to sensor data collection, to control response calculations, to telemetry collection and packetizing. Almost all elements of the computational system are Single Event Latchup (SEL) resistant, with the possible exception of an "alarm clock" which will wake the rover up in the morning and maintain a clock reference, The rover design currently incorporates triple redundancy in the alarm clock, Another design feature allows the rover to wake up when the solar panels are activated by the morning sun. Clock updates are also maintained by communicating with the lander.

All electronics are thermally protected by being enclosed in the Warm

Electronics Box described in the Thermal Control section, below.

The rover's sensors are primarily commercial/Mil-Spec parts. For example, the rover imagers are two commercial CCD's with wide angle lenses mounted on the front of the rover as shown in Figures 8 and 9. The sensors which must be exposed to ambient Mars conditions are being environmentally tested at the component level,

A new proximity sensing technology which is being developed by an OACT technology program is a candidate for use by MFEX. This utilizes the central processor to read out CCD images by direct control of the CCD's clock line. Commercial laser light stripers project vertical light planes ahead of the rover as it moves. When laser light strikes an object, bright points show up in the CCD image. By proper choice of CCD look angle and correlation of the laser points with triangulated range to points in the scene, the rover can identify obstacles, such as large rocks, overhangs and holes, Then autonomous hazard avoidance "behaviors" will drive the rover around the obstacle, Use of this technique also appears promising for ranging to obstacles and for "true ground speed" measurements.

The rover's other sensors are used for hazard avoidance, e.g. if the bogie angle encoders indicate that a front wheel has dropped beyond acceptable limits, the rover can back up and avoid the detected hole. Other sensors for hazard detection include contact sensors on the solar panel, three single-axis accelerometers for vehicle orientation detection, and temperature sensors in the Warm Electronics Box, wheel motors, solar panels, etc. The CCD's, of course, can be used for stereo or monocular imaging as well as for hazard avoidance, providing an alternative to the lander imagery for navigation, and providing images for the various experiments. The rover computer design allows switching between the two cameras for efficient power usage.

The navigation and hazard avoidance software, as well as the data compression, packetization, etc. software, forms the application layer around a simple operating system kernel especially designed for the rover. Navigation utilizes a tuning fork rate gyro and sensors such as the steering potentiometers and wheel motor encoders for dead reckoning. The on-board "behavior control" automatically follows the operator designated heading until an anomaly (such as an obstacle) is encountered.

Then higher level “behaviors” modify the “bee-line” traverse heading algorithm to react to the situation. For example, if the proximity sensors indicate a hazard to the rover’s left, it will turn right to avoid it. After avoiding the obstacle the navigation system again heads directly for the target,

Data from the sensors is sampled at intervals compatible with rover control and hazard avoidance, technology experiment requirements, and computational capability, The computer will compress the imaging data, probably using a block truncation coding algorithm, and packetize it with other data for transmission to the lander.

Telecommunications

Rover telecommunications is planned to be by means of Mil-Spec, half duplex UHF modems operating at about 460 MHz and broadcasting over 1 meter high whip antennas. One modem/antenna is located on the rover, the other on the lander. Both modems and their associated whip antennas are provided by MFEX. The lander data system interface with the modem is through an RS 232 port for simplicity, The modem currently being investigated is from the Motorola R-Net series. It was selected primarily for its low power (it has 100 mW and 300 mW operating modes), and for its Mil-Standard qualification. Because the modem is half duplex the rover/lander telecommunications link has been designed to be controlled by the rover. That is, the rover notifies the lander when it wishes to communicate.

Analysis of the modem has shown that communication is possible over several hundred meters in the worst case, even if the rover goes “over the horizon” from the lander’s view. Communication distances of up to 2 km are feasible in the higher power mode. In order to ensure the maintenance of a communication link the rover will conduct a “heartbeat” check with the lander every time it traverses one-half its body length, If the “heartbeat” signal is not detected the rover will automatically back up one-half body length and try again. The rover will try this several times before invoking other fault recovery actions, which may include continuing the mission assuming that the rover to downlink may still work and/or that lander will continue to image the rover.

The Motorola modem is currently the focus of the new parts JPL "Class [)" qualification process. The modem is qualified for operation at -40°C and for g-levels far in excess of the 50 g's required for landing. Analysis has shown that almost all the modem parts can be expected to be Single Event Latchup (SEL) resistant, which would allow the modem's use in a space flight application. The exceptions are two microprocessor chips. These parts are currently being tested for SEL hardness. If acceptable, the modems can be flown without modification. If the chips fail the SEL test several alternatives are being investigated, including selection of other modems or replacement of the unacceptable parts, Another solution is to operate the modem sparingly, merely risking the relatively remote chance of SEL.

During cruise, rover state information is communicated through the UHF modems and antennas to the spacecraft data system, which retransmits this information to earth. This design eliminates the need for a costly and risky umbilical interface between the lander and rover. The rover status is communicated after launch and before entry into the Mars atmosphere so that the state of the system is known after and before the most traumatic events, Since the rover cannot actually be operated in cruise the state information will be limited to a computer memory readout, thermal measurements, and a check of the UHF data link itself. In order to allow the UHF interface to be used the antennas will be tied down and shielded to prevent excessive EM I from reaching the rest of the spacecraft/rover system.

Power

Rover power is provided by 0.2 square meters of solar array. This is sufficient to power the rover for several hours per sol, even in the worst conditions of atmospheric dust. The array cells are standard, space qualified silicon, and will be purchased in a common buy with the lander solar arrays for cost savings. As a backup and augmentation, 150 MW of primary, Lithium Sodium Dioxide, D-cell batteries are enclosed in the Warm Electronics Box. These batteries are flying in the Galileo probe and will be flown in the Cassini probe so they are flight-ready and very inexpensive. Primary rather than rechargeable batteries were chosen because the mass of rechargeable is prohibitive.

The batteries are not required for the nominal mission, which can be conducted entirely on the solar array. However, the batteries are used to power rover communications during cruise so that a power link between the rover and the spacecraft is not required. The batteries are also used to power night operations of the APXS, and for “emergency boost” if the rover is navigating very rough terrain, The batteries are sized such that the most important rover functions can be accomplished in a few days even if the solar array fails.

Power control is relatively complex. The use of a variety of commercial, flight and Mil-Standard parts means that regulated power at a number of voltage levels is required, DC voltages include ±12 v at 2.5 w, ±5 v at 2.5 w, +24 v at 10 w, +5 v at 10 w, and +9 v at 2.5 w, The independent alarm clock battery is a small $LiSOCl_2$ cell which can run the alarm clock for several years.

Redundancy in power switching is provided by cross strapping between the regulators and batteries, however the complexity thus introduced is being investigated for potential failure modes.

Power is managed to maximize power margin and simplify system design. For example, motor startups are done sequentially to minimize power surges and the CCD proximity sensing system is momentarily powered off during motor startup. The UHF modem is only powered when the rover is standing still. Ail power switching is controlled by the central computer.

Thermal Control

Control of temperatures in the harsh Martian environment is a severe challenge, especially when combined with the need for using low-cost components. Consequently, temperature sensitive elements (electronics and batteries) will be enclosed in a thermally insulated compartment called the Warm Electronics Box, or WEB. Elements outside the WEB will be qualified to withstand ambient temperatures,

Cabling out of the WEB is minimized and all cables between WEB equipment and external equipment are pigtailed at their source. An insulated “igloo” tunnel is provided for cables exiting the WEB. A connector panel is provided outside the igloo tunnel and WEB equipment connectors mate to the external equipment connectors at that panel,

The WEB is planned to be a thermal vacuum enclosure to minimize mass. A proprietary Owens-Corning material is being evaluated for the WEB. The WEB will be heated by the operation of the rover electronics. The idea is to operate the computer and modem from the time the solar panels have enough light to generate power until the sun goes down, raising the temperature inside the WEB, Ideally, this temperature peak, plus the insulating capability of the WEB would prevent the WEB temperatures from dropping below -40°C, the operational qualification temperature of the batteries and electronics. However, preliminary analysis shows that the WEB temperature swings down to between -55° and -60°C at night unless additional heat is provided. The electronics and batteries are unlikely to be able to operate at those temperatures, so the rover would be too cold to wake up in the morning,

Resistive heaters may be used to consume excess solar array power and overheat during the daytime to bias the nighttime temperatures upward. The higher thermal losses at the higher temperatures would result in greater temperature swings which are hazardous to electronic packages. A preferred option is the use of two 1-watt each Radioisotope Heater Units which supply a constant power at all times and limit the day-to-night swings.

Two RHU's are a small enough radiation issue that the launch approval process will only require an Environmental Assessment, which is already required because of the APXS's radioactive alpha particle source. This is in lieu of a very costly Environmental Impact Statement which would be required for RTG's. Additional costs for the RHU's and the Environmental Assessment are being bookkept as a lien in the rover budget pending the final selection of RHU's as a thermal stabilization technique.

Cruise thermal control will be maintained by the MESUR spacecraft as part of its normal thermal control design, This may include a small heater in the rover WEB powered by the spacecraft through a simple umbilical. If RHU's are included in the WEB the heater will probably not be necessary, further simplifying the rover/lander interfaces.

MFEX 1MPLEMENTATI0IWNDUSTR% INVOLVEMENT

MFEX is being conducted as a JPL in-house project because limited funding in the early years, plus the short project cycle and the relatively unproven technologies involved, prevent a system contracting approach. JPL's expertise in small rover R&D is being used to develop the prototypical MESUR Pathfinder rover, which will lead to well specified industry contracts for future rovers. Members of the mobile robotics technology community are being involved as potential experimenters, and can analyze the data returned from Mars to improve future technology directions, Members of the technology community and the aerospace industry have participated in the two workshops to define rover technology experiments.

Much of the fabrication of the SIM and Flight Unit will involve contracted items. An issue remains of how to effectively transfer the technology to the industry which will be building future small rovers for MESUR Network and other Mars surface missions. The MESU R Associate Contractor RFP was released this spring and proposals are to be submitted by the end of May, 1993. Two associate contractors will be selected, and will provide personnel to the MESUR Pathfinder Project for purposes of spacecraft technology transfer. MFEX is investigating the feasibility of funding additional contractor personnel to participate in the development of the rover, thereby transferring rover technology at the same time,

MFEX is also a candidate for technology transfer through industrial partnerships for other space mission and commercial applications, and industry interest is solicited.

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